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Horizontal Branch Models as a Test of Mixing on the RGB

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Abstract. We discuss the impact of mixing and rotation along the red-giant branch (RGB) on the properties of horizontal-branch (HB) stars with emphasis on two problems: the nature of the unexpected blue HB population in the metal-rich globular clusters (GCs) NGC 6388 and NGC 6441 and the cause of the low gravities in the blue HB stars. New stellar models indicate that the sloped HBs in NGC 6388 and NGC 6441 might arise from a spread in metallicity, implying that these GCs may be metal-rich analogues of ω Cen. The low gravity problem can be largely explained by the radiative levitation of Fe in the atmospheres of the blue HB stars. We show that the onset of radiative levitation and the drop in HB rotation velocities at $T_{\rm eff} \approx 11,000$ K coincide with the disappearance of surface convection. The low rotation velocities of the hotter HB stars may be due to the spin down of the surface layers by a weak stellar wind induced by the radiative levitation of Fe. We conclude that the impact of mixing and rotation on the HB remains to be clearly established.

1. Introduction

The abundance anomalies in C, N, O, Na and Al found in red-giant stars in GCs are often attributed in part to the rotationally driven mixing of nucleosynthesized material from the vicinity of the hydrogen shell out to the stellar surface (Kraft 1994). It has been frequently suggested that such mixing and rotation might impact the subsequent HB evolution particularly in regard to the 2nd parameter effect. Perhaps the best evidence for this possibility comes from the 2nd parameter clusters M3 and M13. In M13 one finds evidence for extensive mixing on the RGB, high HB rotation velocities and a very blue HB morphology, while in M3 there is less mixing on the RGB, lower HB rotation velocities and a redder HB morphology.

How would rotation and mixing affect a star's evolution? Since rotation delays the helium flash at the tip of the RGB, it would lead to a larger helium-core mass and greater mass loss. Consequently a rotating star would be both bluer and brighter on the HB than its non-rotating counterpart. In the case of mixing one must distinguish between "shallow" mixing, which does not penetrate into the hydrogen shell, and "deep" mixing, which does. "Shallow" mixing would have little, if any, effect on the HB. In contrast, "deep" mixing into the shell would increase the envelope helium abundance as well as the luminosity (and hence mass loss) at the tip of the RGB. The net effect of both rotation and "deep" mixing is to produce a bluer and brighter HB morphology.

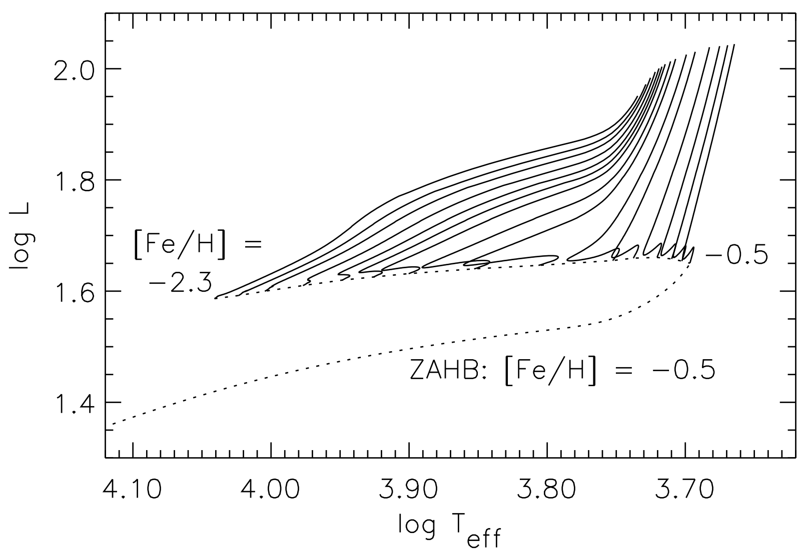

Figure 1. HB tracks (solid curves) for a range in [Fe/H] from −0.5 to −2.3 and for a mass loss parameter $\eta_{\rm R}$ = 0.5. The lower dotted curve represents the canonical ZAHB for a constant [Fe/H] = −0.5.

2. New Results

Rich et al. (1997) discovered that the HBs in NGC 6388 and NGC 6441 possess prominent blue extensions not found in other metal-rich GCs. Quite remarkably, these HBs also slope upward with decreasing $B-V$ from the red clump to the top of the blue tail. Using canonical HB models, Sweigart & Catelan (1998, hereafter SC98) demonstrated that differences in age or mass loss along the RGB - two popular 2nd parameter candidates - cannot explain the HB morphology of these GCs. However, SC98 did find that deep mixing and rotation could produce upward sloping HBs similar to those observed in these clusters.

One scenario not considered by SC98 was a spread in metallicity within NGC 6388 and NGC 6441, a possibility first raised by Piotto et al. (1997). In order to explore this scenario in detail, we have evolved sequences from the main sequence through the HB phase for a range in [Fe/H] from −0.5 (the approximate metallicity of NGC 6388 and NGC 6441) to −2.3. For simplicity we assume that all models are coeval and that the Reimers mass loss parameter $\eta_{\rm R}$ is the same for all [Fe/H]. As shown in Figure 1, the zero-age HB (ZAHB) for these variable metallicity tracks is about 0.4 mag brighter than the canonical ZAHB for [Fe/H] = −0.5 at the top of the blue tail. When translated into the observational (V, $B-V$) plane, we would expect the HB defined by the tracks in Figure 1 to slope upward by about the amount observed in NGC 6388 and NGC 6441. These results suggest that NGC 6388 and NGC 6441 might be metal-rich analogues of ω Cen, the only other GC known to contain a spread in metallicity.

Blue HB stars in the temperature range $4.3 \gtrsim \log T_{\rm eff} \gtrsim 4.0$ generally have lower surface gravities than predicted by canonical models when their spectra are

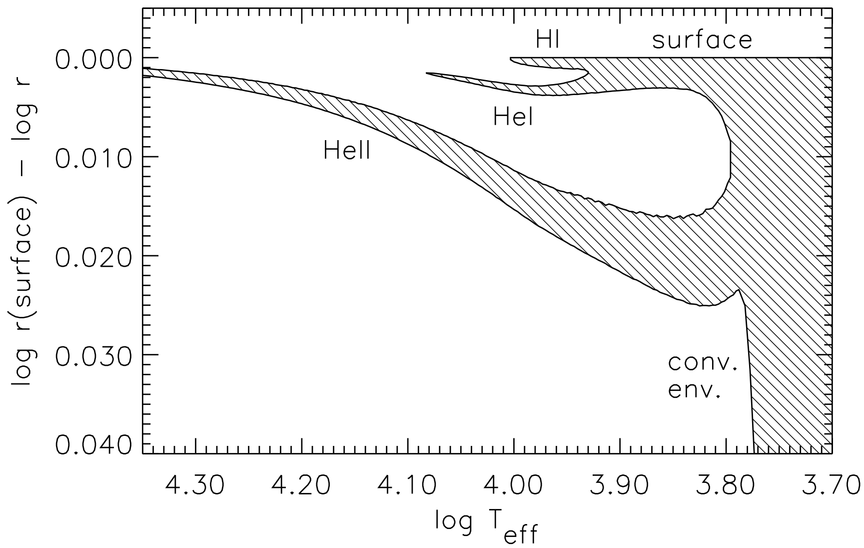

Figure 2. Variation of the envelope convection with $T_{\rm eff}$ along a canonical ZAHB for [Fe/H] = −1.6. Shaded areas are convective. The ordinate gives the depth in radius r into the models.

analyzed using stellar atmospheres with the cluster metallicity. Deep mixing was initially suggested as a possible explanation for this low gravity offset. However, it is now known that radiative levitation of heavy elements can increase [Fe/H] in the atmospheres of these stars to solar or super solar values. Most of the low gravity problem disappears when these stars are analyzed with metal-rich atmospheres (Moehler et al. 2000).

A number of interesting phenomena occur in HB stars around a temperature of $\approx$11,000 K including the onset of radiative levitation, a shift to lower surface gravities, a drop in rotation velocities, a jump in the Strömgren u magnitudes, and in some GCs a gap in the HB distribution. These phenomena may be related to the disappearance of surface convection and hence to the formation of a more stable stellar atmosphere. As illustrated in Figure 2, HB stars cooler than log $T_{\rm eff} \approx 3.8$ have deep convective envelopes. Hotter than this temperature, the envelope convection breaks into distinct shells associated with the ionization of H and He. Note that the surface convection disappears at $\approx$11,000 K.

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